LITHOLOGY OF THE WHITE RIVER SEDIMENTS.

Investigation aided by a grant from the Marsh fund of the National Academy of Sciences.

By HAROLD R. WANLESS.

(PLATES IX. AND X.)

(Read April 22, 1922.)

I. INTRODUCTION.

Since 1847, when the first White River fossil was described by Dr. Joseph Leidy, the abundant and varied fauna of this series, as exposed in the Big Badlands of South Dakota, has made it a center of interest for paleontologists and collectors. During the field seasons of 1920 and 1921 the writer has worked in this area with Professor W. J. Sinclair with the object of tracing the detailed faunal changes and determining, from the lithology of the beds, the conditions of sedimentation through the successive formations which make up the White River series. The work has been carried on in the Big Badlands south and southwest of the town of Scenic in Pennington County, and along the Wall of the Badlands north of Interior in Jackson County.

The earliest investigators assumed that most of the Tertiary mammal-bearing beds of the west were lake deposits, and that the excellent preservation of the skulls and skeletons they afforded was due to protection by water from subaërial weathering and disintegra-

tion. Hatcher was among the first to suggest the possibility of a flood-plain of fluviatile origin instead of lacustrine, and evidence in recent years has been accumulating which supports his hypothesis. We are now able to recognize river-channel, fresh-water pond, sheet-flood, and eolian elements in the series. In the present investigation the writer has endeavored to draw from the lithologic characteristics of the sediments the sources of the material, the methods of transportation and deposition, and the physiographic and climatic conditions under which the White River faunas lived and evolved.

II. Generalized Section of the Big Badlands.

To make the stratigraphic relations of the various types of sediments more clear, a generalized columnar section of the Big Badlands is presented in Figure 1, *C*, correlated with a section of the Oreodon beds from the Wall of the Badlands near Interior, about 40 miles to the east, and with Wortman's 1893[1] section, which has been generally used as the standard section for the district and is now somewhat in need of revision. The datum plane of correlation used is the top of the lower zone of rusty nodules or "Red Layer," as defined below. The stratigraphic elements of the White River series may be briefly indicated as follows:

1. *Titanotherium Beds.*—This zone consists of clay beds with numerous large sandstone channels. Thin limestone lenses are frequent throughout, but caliche zones are rare or absent. The subdivision of the Titanotherium beds into Upper, Middle, and Lower zones in Wortman's section is based on the supposed zonal distribution of titanotheres presenting different stages of horn development, as worked out by Hatcher.[2] A corresponding stratigraphic or lithologic subdivision has not yet been recognized and it is doubtful whether such will ever be possible. The thickness of the Titanotherium beds in the sections measured by our expeditions varies from 110 to 132 feet, which is somewhat less than Wortman's figure of 180 feet, though there are doubtless thicker sections than those measured by the writer, for the Titanotherium beds vary greatly in thickness from point to point, resting as they do on the very irregular erosion surface

[1] *Am. Mus. Bull.,* 5, 1893, pp. 98–9.

[2] *Am. Naturalist,* March, 1893.

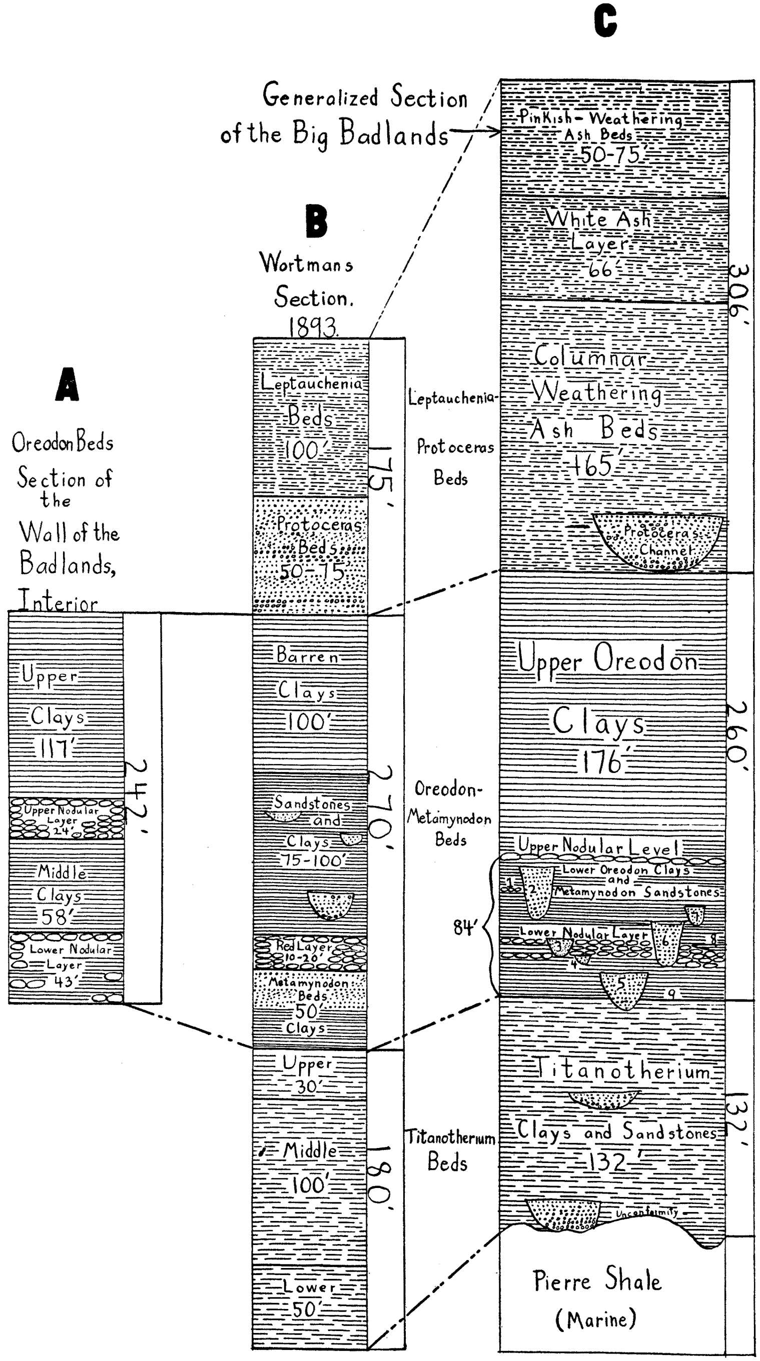

FIG. 1. Correlation diagram of sections of the White River formation. Section C: (1) algal ball horizon, Quinn Draw; (2) Metamynodon channel sandstone, Quinn Draw; (3), (4), (5) and (6) Metamynodon channel sandstones in Corral Draw; (7) Metamynodon channel sandstone, Little Corral Draw; (8) Solid sheet of algal limestone, Little Corral Draw; (9) Thin sheet of silicified limestone at base of Oreodon beds.

FIG. 1. Titanotherium beds topography as exposed in Indian Creek, Big Badlands. Note the rounded character of the hills. The Sheep Mountain section of Oreodon and Leptauchenia beds is seen in the distance to the left.

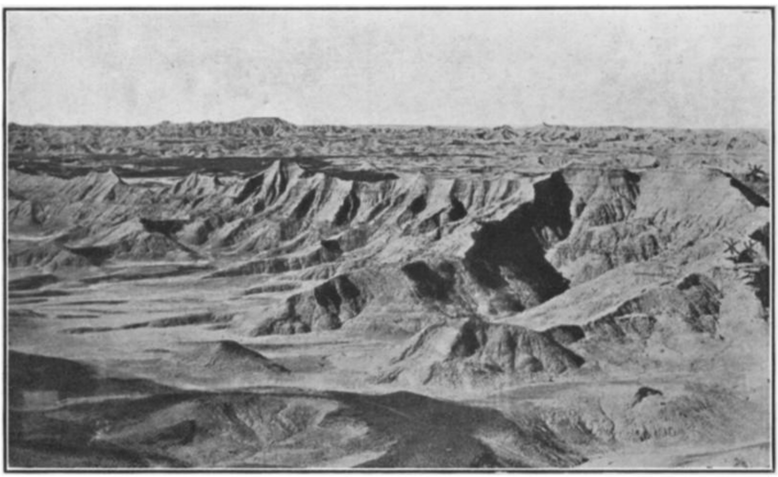

FIG. 2. Section of the Oreodon beds in Corral Draw, Big Badlands. The upper nodular level is marked (*), and the lower zone of rusty nodules or the red layer (**). Photo from the collection of the late S. W. Williston.

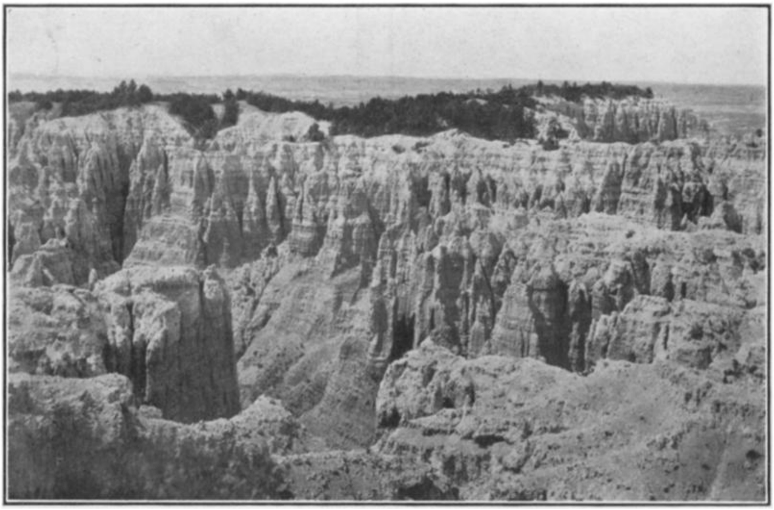

FIG. 1. Section of the Leptauchenia volcanic ash beds in a canyon of Sheep Mountain, Big Badlands. The top of the columnar vertical weathering in the picture is the top of division (*a*) of the Leptauchenia beds, as described in the text. Above this is the "white ash layer" of Matthew, division (*b*) of the text. This appears lighter colored than division (*a*), and does not show vertical columnar weathering.

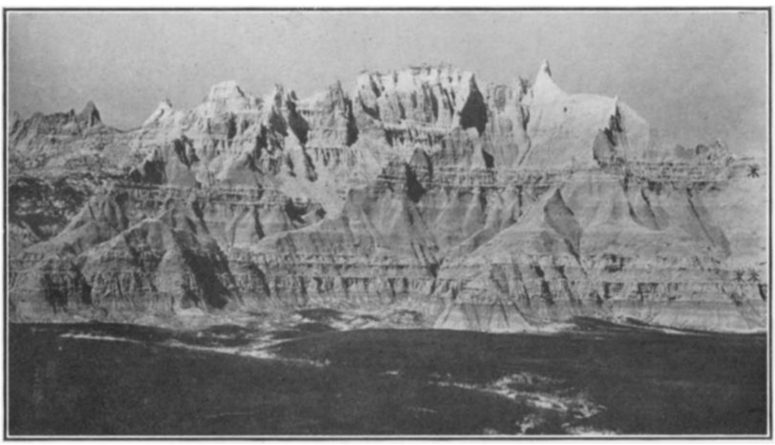

FIG. 2. Section of the Oreodon beds in the Wall of the Badlands at Cedar Pass, north of Interior, Jackson County. The central highest pinnacles are capped by Leptauchenia volcanic ash beds. The subdivision of the Oreodon beds here into upper clays, upper nodular layer, middle clays, and lower nodular layer are clearly shown, especially in the right half of the picture. The upper nodular layer is marked (*) and the lower nodular layer (**).

of the Pierre shale. The lower part of the Titanotherium beds consists of blue and lavender clays made up entirely of reworked Pierre shale and affording calcareous nodules with cone-in-cone structure containing remanie Pierre shale fossils.[3] This lower zone is discussed below in connection with ground water circulation. The channels and limestone lenses are so numerous and, apparently, local that their stratigraphic positions have not been indicated in the generalized section.

2. *Oreodon-Metamynodon Beds.*—(*a*) Wall of the Badlands section. The Oreodon or Middle White River series as generally developed consists essentially of clays with local limestone lenses, interrupted by channels of coarse sandstone containing *Metamynodon.* In the "Wall of the Badlands" section near Interior (Fig. 1, *A*) they are divided into: (*a*) lower zone of rusty nodules and clays; (*b*) intermediate clay zone; (*c*) upper zone of nodules, more generally greenish than rusty; (*d*) upper clay zone. (See Plate II, Fig. 2.) The upper zone of nodules as here developed is absent in the Big Badlands and the same term is there applied to a thin caliche zone which is remarkably persistent over at least 200 square miles and may extend farther yet, but does not occur, or has not been identified, in the Interior section.

(*b*) Big Badlands section (Fig. 1, *C*). The base of the Oreodon beds in the Big Badlands is defined by discontinuous thin bands or lenses of silicified limestone or chert, ranging where present from two inches to one foot thick. This division plane was mentioned by Darton[4] when he first defined the Chadron and Brule formations. Where the limestones are absent the line of change in the weathering between the Oreodon and Titanotherium beds is used for the contact plane. The profiles developed on the Oreodon clays, as a rule, have steep slopes and a more angular appearance, while the Titanotherium beds weather with gentler slopes and more rounded surfaces. Plates I. and II. bring out this contrast clearly.

In the same area, the lower zone of rusty nodules, or so-called Turtle-Oreodon layer or "red layer," is defined by Sinclair[5] as beginning

[3] *Science,* Vol. 19, p. 254, 1904.

[4] Professional Paper, 32, U. S. G. S., p. 71.

[5] PROC. OF THE AMER. PHILOS. SOC., Vol. 40, 1921, pp. 457–466.

with the algal limestone or chert band at the base of the Oreodon beds and continuing upward from 29 to 43 feet (varying with the locality), generally overlain by a more greenish clay or nodule-bearing horizon much poorer in fossils than is the red layer. The red layer consists of pinkish clay with rusty-brown caliche nodules in fairly regular bands or irregularly distributed. In the Indian Creek sections usually from one to three nodule-bearing horizons are found in it, while in parts of Corral Draw as many as ten levels of nodules may occur. Elsewhere, as on Cain Creek, six miles east of Scenic, nodules are locally absent over large areas, and the whole lower Oreodon series consists of clays. As it is often impossible to tell at what part of the lower zone the nodules are developed it has been found that the upper layer discussed at greater length in the paragraph following makes a better datum plane than the lower zone. Both of these zones are very fossiliferous and the intervening clays from the upper nodular level to the base of the Oreodon beds have also produced many important fossils. Professor Sinclair's paper on the "Turtle-Oreodon layer or 'red layer,' a Contribution to the Stratigraphy of the White River Oligocene," which has just appeared, discusses primarily the lower nodular zone, and reference may be made to it for further details.

The upper level of rusty nodules is six inches to one foot thick and 80 feet, more or less, above the base of the Oreodon beds, or 40 to 60 feet above the top of the Lower nodular zone, the variation being due to changes in the thickness of the latter. As mentioned above, this thin zone of nodules is so widely distributed over the area of the Big Badlands that it makes the best datum plane in the whole series of the Oreodon beds. It has been clearly recognized at points separated by 25 miles (Arnold's Ranch district, 12 miles southeast of Scenic and Battle Creek Canyon, 30 miles southwest of Scenic) and may be found to have a still wider distribution.

The channels which cut the lower zone of rusty nodules are characterized by the presence of the large aquatic rhinoceros, *Metamynodon,* and are therefore called Metamynodon sandstones. They cut the Oreodon clays at various levels, but are most numerous between the upper level of rusty nodules and the base of the Oreodon beds. The stratigraphic position of six of these channels is shown in Fig. 1,

Section *C*, which also gives the position of a limestone lens in Little Corral Draw and an algal ball level in Quinn Draw.

The clays above the upper nodular level are generally alternate bands of pale pink and pale green beds with very few channels and nodular layers and no limestone lenses observed. The average thickness of this clay series in the Big Badlands is 160 to 170 feet, with a variation of not more than 10 feet in three sections measured 20 miles apart. This clay zone is less interesting because of its poorer fossil content and has not as yet been studied in much detail. Around the western and southern ends of Sheep Mountain this clay series is capped by a heavy sandy nodular layer about 50 feet thick, but this layer was not observed elsewhere.

3. *Leptauchenia-Protoceras Series.*—*A*. Protoceras Beds. The name Protoceras beds has often been applied to all of the Upper White River, but should be restricted to the stream channels cutting the so-called Leptauchenia clays, the former alone carrying a Protoceras fauna. No channels over 30 feet in thickness have been observed by the writer, and Wortman's figure of 50–75 feet is probably somewhat excessive. The position of these channels is generally at or near the base of the Leptauchenia beds. As the Protoceras sandstones are only formed in stream channels, many sections contain no Protoceras beds at all, the Leptauchenia horizon resting directly on the Upper Oreodon clays. It has been supposed that the Protoceras sandstones were deposited right in the stream channels where the current was strong, while the Leptauchenia "clays" were deposited at the same time in the quieter backwaters. In many samples of Protoceras sandstones, however, water-worn concretions are found, such as are very characteristic of the Leptauchenia beds. These concretions were sufficiently consolidated at the time of the Protoceras channels to be preserved as pebbles in the sandstones formed. This shows that the Protoceras channels were actually cut through the Leptauchenia beds and are thus younger than part of the latter zone. older Leptauchenia beds and are thus younger than part of the latter zone. This suggests contemporaneous erosion of the country rock by the channel forming streams.

B. Leptauchenia Beds. The most complete section of these is in

Sheep Mountain in the Big Badlands. They are subdivided in ascending order into:

(*a*) Vertical, columnar weathering, ash beds often affording abundant nodules somewhat resembling coprolites in shape and size. Each nodule has a vertical central tube around which the nodule seems to have grown by concentric accretion. The cementing material of these nodules has not yet been investigated. The general color of this division is pale pink. Thickness, 165 feet.

(*b*) A massive, white, volcanic ash layer at the top of the zone of columnar weathering, 66 feet thick. This and division (*a*) are shown in Plate II., Fig. 1. This zone is *more* resistant to weathering than (*a*), but does not show vertical faces.

(*c*) A capping of 50 to 75 feet of pinkish nodule-bearing volcanic ash beds, exposed on the highest parts of Sheep Mountain.

This gives a total thickness of 281–316 feet for the Sheep Mountain Leptauchenia beds section. If Matthew[6] is correct in correlating the Sheep Mountain "White Ash" layer with that exposed in the Porcupine Creek section of the Lower Rosebud Miocene, about 20 miles south of Sheep Mountain, divisions (*b*) and (*c*) of the above sequence may belong rather to the Lower Rosebud than the White River. This correlation is at present tentative and must be worked out by a more thorough study of both the stratigraphy and the faunal changes.

Additional stratigraphic details, it is hoped, may be presented in a subsequent paper.

III. Method of Investigation.

The method pursued in the examination of the sediments is essentially that described by Crook.[7] A sample of 50 grams was selected for study and, in the case of the finer sediments, was crushed so that all of it passed through a one-millimeter mesh. This was done in order to allow the acid to act freely on all parts of the sediment, so that all of the calcareous cement would be dissolved. This was

[6] Matthew, *Bull. Am. Mus. Nat. Hist.*, Vol. 23, pp. 169–219, 1907.

[7] Hatch & Rastall, "Textbook of Petrology: The Sedimentary Rocks," 1913, pp. 339–414.

then treated with dilute hydrochloric acid until no effervescence followed the addition of more acid. The residue was then washed and dried at 110° C. and weighed, the difference representing the quantity of soluble cement. The residue was then placed in a beaker and water added to a level 9 cm. above the base of the beaker. This was allowed to stand 10 minutes, in which time all particles with a density of quartz or greater and a diameter greater than 0.01 mm. settled. The liquid with the mud was decanted and this process was repeated until the liquid was clear at the end of 10 minutes. The residue was then dried and weighed, the difference in weight representing the amount of mud in the sample. The residue was then decanted to remove silt. The sediment was covered with 14 cm. of water and allowed to settle for 20 seconds and decanted. This decantation was continued until the liquid was clear, some of the silt being saved for examination. The particles thus separated as silt have diameters of 0.01 to 0.1 mm. All coarser residues, when dried and weighed, represented the sand content of the sample.

In samples containing a noticeable percentage of heavy minerals, the sand residue was treated in a separatory funnel with Thoulet's solution (mercuric chloride and iodide dissolved in water) of a density of 2.95–3.0. By this method the rarer heavier minerals were concentrated and their amount and variety determined. From the heavy concentrate the magnetite was removed by an ordinary horseshoe magnet, and it was found that a fair concentrate of micas for study purposes, without attempt at quantitative separation, could be made by sliding the lighter sands repeatedly from a sheet of paper, where the mica flakes generally remained on account of their flatness.

The sands, silts, and heavy concentrates were then studied microscopically, with a series of liquids of known indices of refraction, and the individual minerals thus determined.

IV. Types of Sediments.

In the sequence of sediments composing the White River series there are: (1) Stream-channel sandstones, represented by those of the Protoceras, Metamynodon, and Titanotherium levels whose relations to the surrounding clays can, generally, be easily deciphered. Due to the superior resistance to weathering of the sandstones, the

courses of old stream channels can often be traced clearly, sometimes by the crest of a high divide, sometimes by a marked ridge of sandstones across a modern creek valley.

(2) Fresh-water limestone deposits. These occur at various horizons through the Titanotherium and Oreodon beds and represent small pond or damp meadow deposits.

(3) Sheet-flood deposits. These constitute the bulk of the sediments of the Badlands and are normally clays not thoroughly consolidated, except where they have been old land surfaces for considerable periods, and have given rise to nodular or "caliche" beds by the drawing up of ground water to the surface where it evaporates, leaving its mineral content as a cement for the clays.

(4) Volcanic ash beds. The term "Leptauchenia Clays" is inappropriate, as the Leptauchenia beds consist essentially of pumice and volcanic glass fragments, connected with the eruptive action of the Cordilleran district during its Tertiary orogenesis. That this ash is probably wind-carried and water-laid, or, at least, reworked by water into essentially horizontal beds of sheet-flood deposition, is the conclusion reached from the strongly marked horizontal bedding of these beds, and the absence of cross-bedding.

(5) Eolian deposits. There are few traces of wind-blown sands in the White River in the area investigated, but one bed has been found in the lower part of the Leptauchenia series in the Sheep Mountain section which seems to be mainly a dune sand, and the sands of the Rattlesnake Butte sand calcite locality are apparently of dune origin, as described by the writer in another paper.[8]

These various types of deposition may now be discussed in somewhat greater detail.

The Channel Sandstones.

Numerous typical sandstones from Titanotherium, Metamynodon, and Protoceras channels were examined. The amount of calcareous cement varied from 14 to 39 per cent., averaging about 25 per cent. In one sample of coarse Titanotherium sandstone, in addition to 26 per cent. of calcareous cement, the grains were found to be embedded in a matrix of chalcedony which may have constituted 10 or 15 per

[8] American Mineralogist, Vol. 7, No. 5. May, 1922.

cent. of the whole. Another sandstone sample, not directly connected with a channel, was nearly uncemented and crumbled readily in the hand. This showed only 2 per cent. of calcareous cement.

As for mineral composition, the grains show very definitely their derivation from the pre-Cambrian schists and pegmatites of the Black Hills. The quartz grains are ordinarily between 80 and 90 per cent. of the total sand and show frequent mineral inclusions, mainly biotite and tourmaline, which, according to Sherzer,[9] are, as a general rule, characteristic of gneisses and schists. The coarser sandstones contain a larger proportion of fresh, non-kaolinized feldspar than is found in the finer silts and clays of the series. Of the grains determined, microcline is the most abundant species; pink orthoclase is next in abundance and the plagioclase feldspars are quite rare, albite and oligoclase-andesine being determined. The feldspars averaged from 5 to 15 per cent. of the sands. Of the micas, white mica and brown mica (muscovite and probably biotite) are the most abundant, but green and black micas also are frequently present. The micas are most abundant in sands with small grains and evidently were laid down in quieter shallows away from the main current of the streams. They may total 1 or 2 per cent., but rarely more.

The heavy residues are more abundant and of larger grain in the coarser conglomeratic phases of the sandstones which contain occasional large quartz and feldspar pebbles. These were evidently formed where the current was strongest, as the finer sediment could not come to rest. The most abundant of the heavy minerals is a pink garnet which generally occurs in good rhombic dodecahedrons or combinations of these with tetragonal trisoctahedrons, or in sharp angular fragments of these crystals. In one sample where the heavy concentrate constituted 3 per cent. of the total sand, the garnet was nearly 90 per cent. of the concentrate. The other abundant heavy mineral is tourmaline, either the black massive variety of pegmatites (schorl) or very small, long prisms of dark brown and green color. The tourmaline never occurs in rounded grains in these sediments. Magnetite is present in some sands to 0.1 per cent. or occasionally more. It is usually in very fine well-rounded grains resembling in

[9] *Bull. Geol. Soc. America,* Vol. 21, 1910, p. 638.

appearance small particles of shot. Staurolite as angular, orange to brown grains is almost always present with the garnet. Other minerals identified in smaller quantities are: Augite (light green grains), rare; pyrite, very rare; hematite, apatite, and amblygonite (lithium phosphate). Other metallic nonmagnetic grains are perhaps cassiterite, wolframite, or columbite, all of which are common minerals of the pegmatite dikes of the Black Hills. In the coarser sandstones are found small pebbles of quartz-schist, quartz-sericite schist, and garnet-biotite schist, and a few pebbles of very fine-grained slates.

The evidence of the composition of the sandstones, as to the derivation of their material, is in full accord with the evidence of the direction of the channels, which lead away from the central granitic core of the Black Hills. Garnet, staurolite, the various schist pebbles, and quartz with inclusions point to derivation from the Algonkian schists and slates of this central core, and the tourmaline, amblygonite, and cassiterite (if present) point to derivation from the pegmatite dikes of the same district. The microcline, augite, and apatite are accessory constituents of the sands and may well have had a similar source.

The channels are evidently of different ages, as shown by their different stratigraphic positions in the accompanying sections, and some horizons seem to be cut by no channels through their whole visible extent. The upper nodular layer is an example of this.

A sample of the channel sand from the stream bed of Battle Creek, near Keystone, in the center of the Black Hills pre-Cambrian core, and within 5 miles of Harney Peak was collected and examined. It corresponds very closely in mineral composition to the stream-channel sands of the White River, but differs in the proportion of minerals present, and is generally of coarser grain, containing more garnets which may reach 30 per cent. of the total sand and more schist pebbles. This would be expected, as the stream is flowing through a garnet-mica schist terrane where the sample was collected. This may be regarded as confirmatory evidence of the Black Hills derivation of the material of the channel sandstones.

Fresh-Water Limestones.

At various levels through the Titanotherium and Lower Oreodon beds are thin sheets or lenses of white limestones. These are some-

times in the form of algal ball levels made up of a series of flattened, oval-shaped balls which are often quite persistent. Elsewhere thin sheets of silicified limestones occur in which the original organic character has been almost destroyed by replacement by secondary silica. Such a sheet as this is sometimes quite persistent at the contact of the Oreodon and Titanotherium beds and, as elsewhere indicated, was used by Darton in defining the contact plane of these two horizons. A third type of limestone forms a lens-shaped solid sheet a few acres in extent. This type develops a limestone as much as 3 feet thick and is quite rich in organic remains, especially the shells of cyprids. This latter type undoubtedly represents a small pond on the surface of the flood-plain. Small pelecypods and gastropods are visible in this, but the fauna has not yet been described. It is believed that one reason for the silicification of the limestone is the solution of the siliceous shells of diatoms and replacement of the lime by this dissolved silica and also the solution of the limestone by ground water and replacement by colloidal silica. The fact that the limestone was in large measure formed by the action of fresh-water algæ was first suggested by Sinclair in 1920 for the algal ball type of limestone.[10] The presence of algæ has since been recognized in the other types of limestone mentioned above. The amount of lime in these beds is very variable, from 5 per cent. in the silicified cherty layer at the base of the Oreodon beds to 95 per cent. in one of the massive lenses of limestone.

The detrital material in the limestones showed the presence of fragments of quartz, biotite and tourmaline, and of pumice needles and angular volcanic glass fragments, suggesting that the detrital deposition in the ponds was probably by wind. It may be that the thinner sheets of algal limestone do not represent pond deposits, but were formed in moist meadow lands under prairie conditions.

Nodular Layers.

The presence of nodular layers is of great interest to the palæontologist, as it is in them that vertebrate remains are best preserved. In some localities the nodules occur more or less isolated, but more often they are found as broad sheets and as such have a remarkable continuity.

[10] Amer. Philos. Soc., Vol. 40, 1921, p. 460.

The essential difference between the composition of the caliche levels and that of the other parts of the clay series is in the proportion of calcareous cement. Samples of the upper and lower zones of rusty nodules analyzed gave, respectively, 51 and 37 per cent. soluble calcareous cement. A nodular layer (not caliche) of more sandy character, but of uncertain origin, in the upper 50 feet of the Oreodon beds, exposed only in the Sheep Mountain sections, contains 30 per cent. of soluble cement. The average amount of soluble cement of the clays of the White River series is from about 5 per cent. in the Titanothere beds to 15 per cent. in parts of the Oreodon series. The caliche nodular layers were doubtless cemented at or near the surface by ground water rising by capillary attraction and depositing the calcium carbonate when it evaporated. Thus the bones of animals which happened to be near the surface at this time were protected from disintegration. The clay forming the nodular layers was originally a fine-grained flood-plain deposit which persisted as a land surface for a considerable period of time and probably indicates a period of greater aridity, by reason of the breaks in deposition, evidence of evaporation, etc. The nodular layer has in the presence of coprolites of carnivorous animals and rodent-gnawed bones absolute proof of subaërial deposition. Many of the bones found are also of a decidedly weathered appearance much as are bones of modern animals weathering on the surface of the Badlands today and occasionally buried in silt. Further proof of subaërial deposition was recently found during the preparation of a *Cænopus* skull collected in the lower zone of rusty nodules, a large number of casts of insect larval burrows being found within and around the skull, suggesting that it had lain on the surface for some time before burial and the meat had been devoured by the scavenging insects, which subsequently burrowed for pupation in the mud investing the skull. It has not been possible yet to determine to what form these insects belonged. The great continuity of the nodular layers, which has been mentioned above, implies a very level surface controlling evaporation, which was cut here and there by shallow winding stream channels, which may have carried running water only in flood time. A uniform climatic factor, probably a period of greater aridity, was one of the most im-

portant elements in the formation of the caliche nodular levels. The part which climate played in the color-banding of the Oreodon clays has not yet been determined.

The clays making up the nodular layers resemble the normal clays very closely. They contain very finely divided silt from the decomposition of the feldspars of the Black Hills, and small angular fragments of quartz of a size smaller than the lower limit of rounding by water. Flakes of brown mica are frequently seen. Fragments of pumice and volcanic glass were recognized in all samples studied and sometimes make up an appreciable per cent. of the total clastic material. These were wind-carried and water-laid, as demonstrated by the marked horizontal bedding of the nodular layers and the absence of cross-bedding.

Volcanic Ash Beds.

The Leptauchenia beds consist largely of a well-consolidated white fine-grained rock, which weathers with a marked vertical columnar appearance, giving rise to sheer cliffs up to 200 feet high. This seems to consist very largely of volcanic glass and pumice. The pumice shows numerous capillary tubes in parallel arrangement which are sometimes deformed by flowage (indicated by strain polarization). There are also throughout the mass long hair-like needles with capillary tubes in the center resembling superficially Pele's hair. With the material of volcanic derivation there are also small fragments of mineral matter of the texture of silts. The grains are not rounded and are mostly too small to be rounded by water. Quartz and biotite are the most common of these mineral fragments, and feldspars and tourmalines were also recognized. A sample of the sand from the White Ash layer, division (*b*) of the beds as described above, which contains about 90 per cent. glass or pumice fragments, was analyzed by Professor A. H. Phillips, of Princeton University, with the following result:

SiO_2	68.21	MgO	1.13
TiO_2	0.32	K_2O	4.41
Al_2O_3	10.97	Na_2O	3.13
Fe_2O_3	2.89	P_2O_5	none
FeO	0.13	$H_2O > 110°$	5.01
MnO	0.12	$H_2O < 110°$	3.05
CaO	1.08		100.45

Calculated in terms of norms as described by Iddings,[11] this glass is a rhyolite with the following standard mineral composition:

Orthoclase	28.36	Diopside	2.38
Albite	28.82	$MgSiO_3$	2.00
Anorthite	2.78	Ilmenite	0.60
Quartz	31.93	Hematite	3.13

In some specimens of these ash beds small cavities and irregular cracks are lined with needle-like crystals of a zeolite, apparently mordenite, of the composition $(Ca, Na, K)_2Al_2Si_{10}O_{24} \cdot 6\frac{1}{2}H_2O$, with a mean index of refraction of 1.465 and a very low double refraction, about .005. This was probably formed as a result of slight hydrometamorphism by alkaline solutions deriving their soluble content from the volcanic ash on which they reacted. There is little chance of thermal metamorphism, as the ash should have been thoroughly cooled after transportation several hundred miles in the air. The cavities in which these zeolites have crystallized are not solution cavities, but more probably shrinkage cracks. The index of refraction of the glass and pumice was found to vary between 1.495 and 1.505. The composition of the zeolite is very similar to that of the ash, and it is probably a recrystallization of material derived from the glass and pumice.

In making the analysis of the ash, Professor Phillips found that after being dried at 110°, to remove the absorbed moisture, on standing in the air the ash took up about 3 per cent. of water very readily. This strong hygroscopic character is probably due to the attraction of the capillary tubes of the pumice fragments for water, and may account in part for the resistance to weathering of the ash beds, as described above.

The Clay Beds.

The greater part of the White River formation is not made up of the more interesting types already described, but rather of very fine silt horizontally bedded and color-banded pale pink or brown and pale green. These constitute all of the Oreodon and Titanotherium beds except the nodular layers, channel sandstones, and limestone lenses.

Their minerals are generally so fine grained as to be difficult of determination, but fine angular fragments of quartz, more or less

[11] "Igneous Rocks," Vol. I., pp. 435 on.

weathered feldspars, and mica foils can be detected in all samples, as well as occasional fragments of pumice and volcanic glass. The latter fact shows that showers of volcanic dust were being deposited throughout White River time, but first became the dominant source of sediment at the beginning of the Leptauchenia beds stage. The clay beds represent the normal sheet-flood deposits of a level country and probably are mainly formed of kaolinized feldspars from the granites and pegmatites of the Harney Peak mass, as well as from decomposition products of other minerals less stable in the zone of weathering.

As mentioned above, the profiles developed on the Oreodon clays, as a rule, have steeper slopes and a more angular appearance than those developed on the Titanotherium beds which weather with gentler slopes and more rounded surfaces. The chemical tests suggest that this is due to a difference in the amount of calcareous cement in the two series. The samples of the Oreodon clays averaged 10 to 12 per cent. soluble cement, while the Titanotherium clays averaged only about 4 per cent.

V. Evidence from Shapes of Sand Grains.

Inasmuch as the method of transportation and deposition of sands can often be definitely established by the shapes and average sizes of sand grains, a study of this feature of the White River sands was attempted.

The channel sands, as a rule, have large rounded grains, but the smaller grains are almost all angular and with sharp conchoidal fracture. This is because grains with a diameter less than 0.1 mm. are coated, while submerged, with a film of water which prevents one grain coming into physical contact with another, and thus prevents abrasion. On the other hand, the air forms no such cushion for the smaller grains, and thus wind-rounded sands may show rounded grains down to the finest sands present. The only sample of sand found in the White River which showed thorough rounding even to the finest particles is a fine-grained sandy silt occurring 11 feet above the base of the Leptauchenia beds in the Spring Draw section, Sheep Mountain. This sand has well-rounded grains even in the smallest sizes and contains a notable amount of magnetite and green horn-

blende, minerals which were not abundant in the ordinary channel sands. The garnets contained in the sand are also well rounded. This bed, which is apparently thin and local, evidently represents dune sand deposition. The sands rounded in stream channels have bright surfaces, while those rounded by wind action generally are dull or show etched or pitted surfaces. The sands of the base of the Leptauchenia bed in the Sheep Mountain section, mentioned above, show dull and pitted surfaces, confirming their eolian origin.

Another excellent example of round-grained dune sand of later age than White River is found in the sand grains of the sand-calcite at Rattlesnake Butte, Washington County. The crystals contain about 37 per cent. calcite, crystallizing as perfect scalenohedrons, and contain perfectly rounded sand grains down to the finest present. The quartz approaches spherical shape, the feldspars are generally larger grains and not quite so well rounded. The pink garnets are round. The green hornblende grains are nearly all elliptical in outline, prisms with the corners rounded. Zircon appears as fine yellow grains, about one fourth the size of the average quartzes. Round fragments of volcanic glass have also been found in this sand. The surfaces of the grains have a dull or ground-glass appearance due to wind abrasion.

By a study of part of the White River in eastern Colorado, Matthew[12] came to the conclusion that the White River was largely of eolian origin. A sample of silt from the Oreodon beds of Lewis Creek, Colorado, in the area investigated by Matthew, was examined by the writer and was found to consist largely of fine dust with much volcanic material (pumice and glass) and some of the quartz grains well rounded. It was evidently mainly of eolian origin. Matthew points out that in much of the fossil material from the White River of northeastern Colorado the "hollows in the bones (such as the cellular hollows in the skull . . ., the tympanic bullæ . . ., etc.) are still empty, never having been filled by mud or crushed in."[13] He points out that this could not happen if the bones were fossilized in such a body of water as a lake, as the weight of water and overlying sediment would either fill in the cavity with mud or crush the skull.

[12] Matthew, *Am. Naturalist*, Vol. 33, 1899, pp. 403–408.

[13] Matthew, *Am. Mus. of Nat. Hist. Memoirs*, Vol. I., p. 365.

Thus it seems that while the White River may be mainly of eolian origin in Colorado as Matthew has decided, it was mainly deposited by fluviatile agents in the South Dakota section. The writer's conclusion is that in the sections of the Big Badlands investigated eolian deposition is unimportant, though locally present.

VI. Evidence of Ground Water Circulation.

Though the clay beds of the Badland district seem to be nearly impervious to water, there are abundant evidences of deposition and replacement by the action of ground water. The formation of caliche nodules by deposition of calcareous cementing material with the evaporation of the water at the surface has been referred to.

Throughout the Big Badland district are veins of blue chalcedony in vertical cracks in the clays. These were probably deposited in shrinkage cracks. Other fissures filled with sandy silts or sandstones occur frequently through the Badlands, but most abundantly in the Leptauchenia beds. These filled fissures are often more resistant to weathering than the surrounding clays and stand out in relief as sandstone dikes. Often the sandstone dikes were bordered on each side by chalcedony veins, and in one case there were two or three veins of chalcedony on the same side of the dike, indicating repeated opening of the fissure. The chalcedony veins ordinarily vary in thickness from one quarter inch to three inches and show evidence of gradual filling of the cracks from the two walls. Sometimes the whole vein is silica, but in many cases, specially in the wider veins, well-formed crystals of calcite have formed in the center of the vein, evidently as the last stage of deposition. Sometimes the center of the vein remains open. Occasionally large bell-shaped concretions of chalcedony up to a foot in diameter are formed in the clay. Chalcedony of similar nature is found filling the marrow cavities of fossil bones and the pulp canals of teeth. An interesting case was noted by the writer in a bone in which the lower part of the marrow cavity was filled with fine silt, evidently worked in soon after deposition, and the rest of the cavity was filled with chalcedony. In several cases chalcedony veins were found to cut directly through fossil skulls. Generally no hardening of the clays adjacent to the chalcedony veins is observed, showing that the deposition was from cold water. Some

diffuse cementation of the clays by colloidal silica in the vicinity of chalcedony veins is occasionally noticed, rapidly wearing the edge off the chisel used in the preparation of a specimen.

In many places the basal titanotherium beds contain a series of about 30 feet of clay of blue, lavender, and pink colors when fresh, weathering to a limonite brown and hematite red. This clay is clearly derived from a reworking of the Pierre shale material and even contains Pierre shale fossils, as Baculites, Inoceramus, etc., which are remanie or redeposited as first reported by Loomis.[14] In places where this series is absent, the silts or sands resting directly on the Pierre shale are almost always colored a bright pink color, and on examination the clay particles are seen to be strongly colored by the red oxide of iron.

The uniform presence of these iron-colored beds at the base of the more or less pervious Titanotherium beds and directly above the impervious Pierre shales is evidently a case of iron dissolved out of the White River series and redeposited and concentrated at the limit of downward circulation along the Pierre shale contact.

VII. Conclusions Drawn from the Lithogenetic Evidence.

From the evidence above presented one can draw a fairly good picture of the physiographic conditions at the time of the deposition of the White River beds.

The country was very level, with a gradual slope away from the Black Hills uplift, as evidenced by a slight initial southeast and easterly dip of the beds. The Black Hills were probably still being elevated, but already were sufficiently high and eroded to furnish clastic material from the pre-Cambrian central core.

Fairly sluggish streams meandered across the plain in shallow channels and frequently spread widely out upon the plain when in flood, depositing thin sheets of fine silt. Gradually increasing volcanic action in the Cordilleran region and perhaps in the northern Black Hills furnished a growing supplement to the clastic material from the hills, until in the Leptauchenia stage this source became predominant. It is possible that the statements of Ransome, Schuchert, and others that the Oligocene represents a lull in the uplift and

[14] *Science*, Vol. 19, p. 254.

vulcanism through the Tertiary Cordillera between the periods of storm of the Eocene and Miocene will have to be amended. The presence of a 200-foot bed mainly of volcanic glass and pumice 80 miles away from the nearest possible source of volcanic ejecta, and more likely 200 to 400 miles distant from the eruptive volcanoes, would hardly seem to indicate a period of quiet. Professor Sinclair's description of a considerable thickness of andesitic tuffs and breccias of Titanotherium beds age in the Wind River Basin of Wyoming south of the Bridger-Owl Creek Range, is interesting in this connection.[15]

The only evidence of vegetation found fossilized so far in the Big Badlands are a few hackberry seeds (Celtis), but Hatcher reports the remains of a forest 12 miles north of the mouth of Corn Creek. The plain was here and there dotted with small ponds in which fresh-water algæ and cyprid crustaceans were building up the limestone beds of the series.

Thus we have a general picture of the environment of one of our finest Tertiary mammalian faunas.

Graduate College,
Princeton, N. J.

[15] *Bull. Am. Mus. Nat. History,* Vol. 30, 1911, pp. 99–102.